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Prospects of Discovering the Higgs Boson at the Tevatron

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Abstract

We carry out an event generator based study to evaluate the usefulness of the the exclusive signature "$e^{\pm}(\mu^{\pm}) + 2$ bottom jets" in discovering the Higgs boson at the Tevatron. Using an event generator, we show that with enough luminosity, one should be able to detect the Higgs boson up to the mass of about 130 GeV. We consider a slightly modified version of the above signature that includes one extra jet. This new signature is more useful because it increases the number of signal events significantly.

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I. Introduction

Discovery of the Higgs boson will be one of the most momentous event in the history of physics. It will validate one of the most important ingredient of the standard model paradigm: the Higgs mechanism. Higgs mechanism is now taken for granted in even various attempts to go beyond the standard model; however experimental evidence for this mechanism remains tenuous at best. In the experiments that are expected to be carried out in the next decade, it is mostly at the LHC where one expects to find the Higgs boson, if it exists at all. However, before enough data is collected at the LHC, it may be possible to detect the Higgs boson at the Tevatron, if the Higgs boson exists in a specific mass domain. This mass domain is the lower intermediate mass region ($M_Z < M_H < 130 - 140$ GeV). It is therefore of utmost importance that the various signatures of the Higgs boson should be studied in as realistic a way as possible in this mass region at the Tevatron. There exists a lower bound on the mass of the Higgs boson of order 90 GeV from the LEP [1]. It is expected to go up to about 100 GeV. The lightest Higgs boson in a class of supersymmetric theories is also expected to have a upper bound of the order of 160 GeV. All these bounds suggest that the intermediate mass region of the Higgs Boson is a very important region. In this Communication, we focus on the lower intermediate mass Higgs boson and analyze a specific signature at the Tevatron. The Higgs boson that we study is the Higgs boson of the standard model. In some of the extensions of the standard model, the properties of some scalar particles are similar to the standard model Higgs boson, therefore our results will also be applicable in that situation.

The useful signatures of a particle at a particular collider depends upon the possible production mechanisms and the decay properties of the particle. There are a number of important mechanisms for the intermediate mass Higgs boson production at a hadron collider. However two of the mechanisms, $p\bar{p} \to HX$ and $p\bar{p} \to t\bar{t}HX$, which are expected to be quite useful at the LHC [2,3,4] are not that useful at the Tevatron. This is because the cross-sections for the Higgs boson production through these mechanisms at the Tevatron are quite small. For example, for the Higgs boson of 100 GeV mass, the cross-sections at the Tevatron ($\sqrt{s} = 2$ TeV) are about 0.54 pb and 1.9 x 10^{-3} pb respectively for the above production mechanisms. Therefore, with the expected luminosity, rare decay channels of the Higgs boson for $p\bar{p} \to HX$ and any decay channel for $p\bar{p} \to t\bar{t}HX$ will give rise to very few if any events at the Tevatron. In this Communication, we specifically consider a third production mechanism where a Higgs boson is produced in association with a W-boson:

$$p\bar{p} \to WHX\,. \tag{1}$$

In the lower intermediate mass region, the Higgs boson decays predominantly into two bottom quarks while the W-boson decays into two leptons, $l^{\pm}\nu_l$, or two quarks. Here 'l' can be an electron, a muon, or a tau-lepton. The useful signatures th[5,6,7,8] through this mechanism require that the W-boson decays leptonically. The signature "$e^{\pm}(\mu^{\pm}) + 2$ bottom jets"due to this mechanism has been studied in detail using parton level Monte-Carlos as well as event generators at the LHC. One event generators based study suggests that a modified version of this signature could be useful. We shall study this same signature at the Tevatron. This signature requires the identification of the bottom jet. Using silicon-vertex detectors, it is possible to identify a bottom jet with an efficiency factor of about $40-50\%$ [9]. However, one also has to take into account the possibility of a jet due to a parton other than the bottom quark mimicking a bottom jet. This would mean that even processes without a bottom jet can be a background to the signature in which we are interested. Therefore a study should include all such backgrounds.

The parton level Monte-Carlo analyses primarily use tree level cross-sections and distributions for the signal and the various backgrounds. The effects of radiative corrections, hadrionization and a lot of other details of an event are not simulated. Such studies are often quite useful as a first step, but in the end to find the feasibility of a signature, a more realistic study is needed. In this Communication, we have carried out a study after including a few background processes in the event generator PYTHIA [10] to take into account major effects of the next-to-leading-order (NLO) corrections. It turns out that one should look at a modified version of the signature that has been considered until now.

The unmodified version of the exclusive signature that we study is "$e^{\pm}(\mu^{\pm}) + 2$ bottom jets". Here by exclusive, one means that we veto any event that has extra hard particles other than an isolated charged lepton and two bottom jets in a particular kinematic domain. Therefore any process that can give rise to a W-boson and two bottom jets with the W-boson decaying leptonically is a background. As discussed above, another source of background is due to flavor misidentification. A gluon or light quark-initiated jet can mimic a bottom jet with a small probability; we therefore also consider processes that give rise to potential backgrounds due to this misidentification. The modification of this signature that we introduce is discussed below.

The background processes are broadly speaking are of two types [7]: the W-boson-associated backgrounds and the top-quark-associated backgrounds. The W-boson-associated backgrounds are:

$$p\bar{p} \to Wb\bar{b}X, \;\; WZX, \;\; WjjX \tag{2}$$

Here the $p\bar{p} \to WZX$ is a background when the Z-boson decays into a pair of bottom quarks. The process $p\bar{p} \to WjjX$ is background when a jet mimics a bottom jet. The signal process $p\bar{p} \to WHX$ is already a part of the PYTHIA package; so is the process $p\bar{p} \to WZX$. We have included the processes $p\bar{p} \to Wb\bar{b}X$ and $p\bar{p} \to WjjX$ in PYTHIA. The inclusion of all the above processes in PYTHIA allows us to study the effects of part of the NLO corrections to the leading-order (LO) results.

The second class of backgrounds, the top-quark-associated backgrounds are:

$$p\bar{p} \to t\bar{t}X, \;\; tbX, \;\; tqX, \;\; tqbX. \tag{3}$$

These processes are backgrounds when the top quark decays into a W-boson and a bottom quark. The primary motivation to look for an exclusive rather than an inclusive signature is due to the $pp \to t\bar{t}X$ background. This process always have particles other than a e/μ and bottom quarks in the final state. Therefore by requiring that there be only a few jets in the final state, we can reject large fraction of the top quark background. Here the process $p\bar{p} \to t\bar{t}X$ is already in PYTHIA. The last three processes are not in PYTHIA. These processes are not most important sources of the backgrounds at the Tevatron but are not insignificant. We are including these processes also in PYTHIA and shall present the results in a more complete study elsewhere. More details about all the above backgrounds can be found in Ref [7].

Although we are using an event generator which provides a means to include some of the NLO effects, but the cross-section of a process is still normalized to the leading order result. This type of Monte-Carlo simulation usually includes only bremsstrahlung-type corrections and the effects of hadronization; inclusion of loop-corrections is not possible in most event generators as is the case with PYTHIA. However, our interest is in that part of NLO corrections that gives rise to extra soft jets, for which purpose PYTHIA can serve fairly well. One can multiply by an overall K-factor to get proper normalization of the cross-section. The QCD corrections to the signal production have been found to be about 10–15% [11, 12]. While for the backgrounds, the corrections will depending on the process These corrections could vary in the range of 10–30% [13]. Therefore the estimates of our signal and background events should be increased by about 10–15% on average. Since at the Tevatron the number of signal events is at premium, therefore a proper appraisal of a signature should include this factor.

The paper is organized as follows: In the next section, we describe how the parton level results change due to the inclusion the NLO effects which are normally included in an event generator. In Sec. III, we discuss the numerical results for the various processes. In this way, we assess the usefulness of the modified exclusive "$e^{\pm}(\mu^{\pm}) + 2$ bottom jets"signature. In Sec.IV, we present our conclusions.

II. Effects in Event Generators

In our analysis, we have used the event generator PYTHIA to take into account some of the NLO corrections. Such event generators have three new ingredients:1) the initial-state radiation (ISR), 2) the final-state radiation (FSR), and 3) hadronization and decays (H & D). As is obvious from the terminology, the initial-state radiation corresponds to the emission of the partons or leptons from the initial-state particles; the final-state radiation is similar emission from the final-state particles; hadronization and decays corresponds to the hadronization of the partons and subsequent decays of the hadrons.

We can illustrate the effects of the new ingredients on the parton level results by considering the signal. In PYTHIA, we can turn-off all these effects and turn-on one new effect at a time to assess its impact on the leading order results. We are starting with the process $p\bar{p} \to WHX$. At the leading order, at the parton level, we have an electron and two bottom quarks in the final state (apart from the partons that do not take part in the hard scattering). When we turn-on the initial-state radiation, it changes the structure of events. A large fraction of events will have more than two hard partons (bottom quarks) in the final state. Therefore, even with a minimum p_T cut on the partons, we shall have a significant numbers of events with more than two jets in the final state. At the Tevatron, *e.g.*, about $40-50\%$ of events will have one or more extra jets (other than two bottom jets) with a p_T cut of about 15 GeV. Therefore, there will be a reduction in the number of signal events, as compared to the leading order, if we consider the exclusive signature "$e^{\pm}(\mu^{\pm}) + 2$ bottom jets". One obvious way to get around this problem is to broaden the signature to include even events with one or more extra jets. The negative aspect of this new signature is that there will be a larger background from processes that have more than two jets without any initial state radiation, *e.g.*, $p\bar{p} \to t\bar{t}X$. Luckily at the Tevatron the top-quark-associated backgrounds are not as dominant as the W-boson-associated backgrounds. The impact of the final-state radiation is similar to that of initial-state radiation with a few differences. Now suppose there is only final-state radiation. There will be fewer events with extra hard jets as compared to the initial-state radiation; this is because of the smaller scale of radiation. However now the mass of two bottom-jet system will be broader and the peak of the distribution will be shifted to a lower value than without the final-state radiation. This is because the final-state radiation would come from bottom quarks (which in turn are there because of the decay of the Higgs boson) and therefore it will drive the $M(bb)$ peak away from the m_H mass. Since W-boson-associated background will increase due to this, the final-state radiation leads to increase in the overall background. One can attempt to improve upon the situation by including extra jets in the mass distribution; so one may wish to make a cut on $M(bbj)$ or $M(bbjj)$ distributions also. The effect of the hadronization and decays is also to dilute the parton-level results. This also shows up as pulling the $M(bb)$ distribution peak below the Higgs boson mass and broadening of the distribution. Lowering of the distribution peak enhances the W-boson-associated background; while a broader distribution increases all backgrounds if we wish to maintain a large number of signal events.

Because of above changes the *modified* signature that we shall consider will be to also include events that have one extra jet (other than two bottom jets). This will increase the number of signal events, but also the total background events. But since it is important to enhance the number of signal events, we use this modified signature. One can consider more than one extra jet also, but it will lead to significant increase in the top-quark associated backgrounds.

III. Numerical Results

In this Section, we present an estimate of the signal and background events rates at the Tevatron. We take the center of mass energy to be 2 TeV. If we apply the following typical acceptance cuts,

$$
\begin{aligned}
p_T^{\ell} > 10 \text{ GeV}; \qquad p_T^{b,j} > 15 \text{ GeV}; \qquad |\eta|^{\ell,b,j} < 2.5; \\
\Delta R(\ell, b) > 0.7; \qquad \Delta R(b, b) > 0.6;
\end{aligned}
\tag{4}
$$

where the index ℓ stands for either electron or muon; η is pseudo-rapidity and $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, we find that the approximate cross-sections are: $\sigma(p\bar{p} \to WHX) = 0.2$ pb ($m_H = 100$ GeV); $\sigma(p\bar{p} \to Wb\bar{b}X) = 5.2$ pb; $\sigma(p\bar{p} \to WZX) = 2.6$ pb; $\sigma(p\bar{p} \to WjjX) = 660.1$ pb; $\sigma(p\bar{p} \to t\bar{t}X) = 6.4$ pb. As we clearly see that combined cross-section for the backgrounds is three-four orders of magnitude higher than the signal. However, the $p\bar{p} \to WjjX$ cross-section, when multiplied by the mimic probability and other cross-sections when multiplied by appropriate branching ratios, we find that the combined background is about two orders of magnitude higher than the signal.To reduce that background further, the useful physical quantities are: $p_T^{b,j}$, $\Delta R(b, b)$, $M(bb)$, $\cos(\Delta\phi)$, $\cos_{CM}^{REC}(H)$. Here $M(bb)$ is the mass of two-bottom-jets system; $\cos(\Delta\phi)$ is cosine of the difference of the azimuthal angle of the two bottom quarks; $\cos_{CM}^{REC}(H)$ is the angle of the two bottom quark system with the z-axis in the reconstructed center-of-mass frame. Because of the existence of a neutrino and soft particles in the final state, we cannot go the center-of-mass frame. However, by deducing the unknown longitudinal momentum of the unobserved particles, as discussed in Ref [7], it is possible to reconstruct approximate center-of-mass system.

The observable $M(bb)$ is most effective. Therefore we shall first consider only acceptance cuts and a cut on the $M(bb)$ observable. We shall briefly discuss the usefulness of other observables towards the end of this section. As we discussed in the last section, the final-state radiation and hadronization & decays shift the $M(bb)$ peak below the m_H mass for the $p\bar{p} \to WHX$ process. Therefore to include most of the signal, we look for events around the shifted peak that is approximately around $m_{peak} = m_H - 20$ GeV. We are displaying the results for $|M(bb) - m_{peak}| < 10$ and 15 GeV in Tables 1 and 2 respectively. The smaller value of 10 GeV will reduce the background, but it will also reduce the signal. Since at the Tevatron, the number of signal events is quite small, therefore it may be necessary to choose a value of 15 GeV for this cut. To arrive at the numbers in the tables we have taken the mimic probability to be one percent and the bottom-jet identification efficiency to be about 45%. The extra-jet can have $p_T > 8$ GeV and $\Delta R(b,b) > 1.2$; rest of the cuts are as in equation 4. Here we have taken the integrated luminosity to be 10 fb^{-1}, which may take several years for the Tevatron to accumulate, until the Tevatron start operating in high luminosity mode. However, we see that one may need about 20 fb^{-1} before one may be able to detect the Higgs boson in the lower-intermediate-mass region. Only with such integrated luminosity, one may be able to achieve a significance ($S/\sqrt{B}$) value of about 3.

Since one of the problem at the Tevatron is to have enough signal events, we would like to comment briefly at the maximum possible number of events for the signature under consideration. We would like to make several points: a) When the W-boson decays into a τ-lepton and it subsequently decays about 35% of the time into a e/μ, this decay-chain will contribute to the signal events (and also similarly to the background); since the electron/muon from a decay chain will be somewhat softer, conservatively, we may expect that W-boson decaying into a tau-lepton will contribute about 25% of the events as compared to when the W-boson decays directly into an electron or a muon; b) The cross-sections that we have used are leading-order cross-sections; It is known that the NLO corrections will enhance the signal at most by about 15% (the backgrounds will also be enhanced by about the same order); c) We have not tried to find the optimum set of cuts; if one tries and uses neural-net or decision-tree like techniques, the signal may still be further enhanced by $15-20\%$; d) the bottom-jet identification efficiency could be as high as about 50% and one may be able to reconstruct the jet better; this may increase the event rate by $10-15\%$; e) one may include events with two or more extra jets; but this will increase the top-quark-associated backgrounds a lot. In Table 3 we display the estimate of the signal and the backgrounds including the a) and b) enhancements (potential enhancement c) and d) and e) are not included).

From these tables we notice that the most troubling background is $p\bar{p} \to Wb\bar{b}X$. This is so large in part because of the peak-shift and broadening of the $M(bb)$ distributions for the signal. The observables $\cos(\Delta\phi)$ and $\cos_{CM}^{REC}(H)$ can help us to reduce this background.($\Delta R(b,b)$ and $p_T^{b,j}$ are also useful. But their effects can be taken care by $\cos(\Delta\phi)$ and $M(bb)$ distributions respectively.) In Ref [7] these distributions were discussed. We find that it is possible to reduce the $p\bar{p} \to Wb\bar{b}X$ background by $50-70\%$ with a reduction in the signal events of about $25-30\%$. However, it does not enhance the significance by a large factor because of small number of signal events to begin with. A more complete study is required to put these and other such observables to optimum use.

IV. Discussion and Conclusions

In this Communication, we have studied the *modified* exclusive signature "$e^{\pm}(\mu^{\pm}) + 2$ bottom jets" for the associated production of the lower-intermediate-mass Higgs boson. This modified signature includes an extra jet. Such a signature results through the process $pp \to WHX \to \ell\nu_\ell b\bar{b}X$ when we include the NLO corrections. Our study is based on the PYTHIA event generator. We have considered the principal backgrounds and found that with enough luminosity one should be able to detect the Higgs boson if it exists in the studied mass region. At the Tevatron, the dominant background is due to $p\bar{p} \to Wb\bar{b}X$. However it can be controlled with judicious choice of cuts. We have not attempted to find optimum set of cuts; however one can use the observables discussed here and in the Ref [7] to reduce the background further. As we see that there is a need to enhance the number of signal events. By modifying the cuts on the observables, one may be able to enhance the signal by at most extra $20-30\%$ as compared to the numbers given in the Table 3. However the background will also increase and one will have to strike a balance to enhance the significance of the signature. The accumulated integrated luminosity will be critical for the detection of the Higgs boson. It would appear that one will need about 20 fb^{-1} of accumulated luminosity before something definite could be said about the existence of the Higgs boson in the lower intermediate mass region. Such a luminosity may be reached if the Tevatron runs in high luminosity mode for several years. A more complete study is underway.

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Processes	M_H 90 GeV	M_H 100 GeV	M_H 110 GeV	M_H 120 GeV	M_H 130 GeV
WH	32	23	16	11	6
Wjj	12	10	8	7	6
Wbb	160	130	99	75	54
WZ	41	32	15	6	3
$t\bar{t}$	17	15	15	15	15

Table 1. Event rates at the Tevatron with 10 fb^{-1} of accumulated integrated luminosity with the acceptance cuts given in the text and $|M(bb) - m_{peak}| < 10$ GeV.

Processes	M_H 90 GeV	M_H 100 GeV	M_H 110 GeV	M_H 120 GeV	M_H 130 GeV
WH	39	29	21	14	8
Wjj	16	13	12	10	8
Wbb	211	170	140	112	91
WZ	52	42	25	10	4
$t\bar{t}$	23	25	23	23	23

Table 2. Event rates at the Tevatron with 10 fb^{-1} of accumulated integrated luminosity with the acceptance cuts given in the text and $|M(bb) - m_{peak}| < 15$ GeV.

Processes	M_H 90 GeV	M_H 100 GeV	M_H 110 GeV	M_H 120 GeV	M_H 130 GeV
WH	51	38	27	18	11
Wjj	21	17	14	13	11
Wbb	271	221	182	146	117
WZ	67	55	32	13	4
$t\bar{t}$	30	32	30	30	30

Table 3. Event rates at the Tevatron with 10 fb^{-1} of accumulated integrated luminosity with the acceptance cuts given in the text and $|M(bb) - m_{peak}| < 15$ GeV. The number also include the enhancement due to tau-lepton decays and the NLO K-factor.